on possible nuclear-physics avenues offered by a Orsay-hosted 450-MeV PERLE version

David Verney, IPN Orsay
An unconventional (and somewhat provocative) introduction

The untold legend of the human quest for ultimate components of matter

The outermost Aristotle’s sphere
"The final cause, then, produces motion by being loved, but all other things move by being moved"
Aristotle Metaphysics 1072b4

SU(3)×SU(2)×U(1)

SU(3)×SU(2)×U(1)

the hidden paradigm of material science: smaller ≈ more “fundamental”

• the historical surprise of finding “complexity” in the microscopic world
• all the colorful beauty and diversity of the observable world is not due to elementary objects but to medium effects

emergence (presently addressed through effective theories)

some foolish people remained stuck at this reputed unessential level of organization of matter why?

10⁻¹⁳ m
down strange bottom photon
10⁻¹⁴ m
10⁻⁹ m
10⁻⁸ m
10⁻⁶ m
10⁻⁵ m
10⁻³ m
10⁻¹ m
10⁰ m
10¹ m
10³ m
10⁻¹ m
10⁻⁸ m
10⁻⁹ m
10⁻¹⁰ m
10⁻¹¹ m
10⁻¹² m
10⁻¹³ m
10⁻¹⁴ m
The "single-particle" concept

\[ \mathcal{H}_{CM} = \mathcal{O}H + U(r)(\hat{\ell} \cdot \hat{s}) \]

E. P. Wigner  
Maria Goeppert-Mayer  
J. Hans D. Jensen

Nobel price 1963

[Diagram showing nuclear levels and single-particle states]


cross sections
The “single-particle” concept

\[ \mathcal{H}_{CM} = OH + U(r)(\vec{l} \cdot \vec{s}) \]

Nobel price 1963

E. P. Wigner
Maria Goeppert-Mayer
J. Hans D. Jensen

Schmidt lines

Mayer et Jensen Elementary theory of nuclear shell structure

**Fig. I.4.** Magnetic moments of nuclei with odd \( Z \) plotted against the spin.

**Fig. I.5.** Magnetic moments of nuclei with odd \( N \) plotted against the spin.
The e-probe revolution

e momentum transfer $q \approx 1/\lambda$.

The interior of the nucleus became accessible!

A(e,e) elastic cross section

$$\frac{d\sigma}{d\Omega}_{eA\rightarrow eA} = \frac{d\sigma}{d\Omega}_{\text{Mott}} \frac{1}{1 + \frac{2E_m}{M} \sin^2(\theta/2)} |F(q)|^2$$

form factor

Fourier transform

charge distribution

12 orders of magnitude!

B. Frois and Papanicolas

Dechargé and Gogny
PRC 81 (1980)

Cavedon, Frois, Goutte et al.
PRL 49 (1982)

etc...

T. Suda, H. Simon
Progress in Particle and Nuclear Physics 96 (2017) 1
The e-probe revolution

A(e,e') inelastic cross section

\[
\frac{d\sigma}{d\Omega} = \sigma_0 \eta \left[ \sum_{\lambda=0}^{\infty} \frac{q^4_\mu}{q^4} |F_\lambda^C(q)|^2 + \left( \frac{q^2_\mu}{2q^2} + \tan^2 \theta \right) \sum_{\lambda=1}^{\infty} \{ |F_\lambda^E(q)|^2 + |F_\lambda^M(q)|^2 \} \right]
\]

point charge nucleus
longitudinal form factor
recoil factor
transverse form factor

\[
\rho_\lambda(r) = \int \langle \psi_f | \rho_{op}(\hat{r}) Y_\lambda(\hat{r}) | \psi_i \rangle \ d\hat{r}
\]
charge transition density

\[
B(E\lambda) = \frac{2J_f + 1}{2J_i + 1} \left[ \int_0^\infty \rho_\lambda(r) r^{\lambda+2} dr \right]^2
\]

\[
J_{\lambda\lambda}(r) = \frac{i}{c} \int \langle \psi_f | \mathbf{J}_{op}(\hat{r}) \cdot \mathbf{Y}_{\lambda\lambda}(\hat{r}) | \psi_i \rangle \ d\hat{r}
\]
current transition density

\[
B(M\lambda) = \frac{\lambda}{\lambda + 1} \frac{2J_f + 1}{2J_i + 1} \left[ \int_0^\infty J_{\lambda\lambda}(r) r^{\lambda+2} dr \right]^2
\]

\[\mu \approx F_M \text{ for } q \to 0\] (elastic at 180°)

30% quenching (again!)

Fig. I.5. Magnetic moments of nuclei with odd \( N \) plotted against the spin.

\[\mu_N = -1.91, \ j = 1 - \frac{3}{2}\]

\[\mu_N = 0, \ j = l \pm \frac{1}{2}\]

\[\mu_N = -1.91, \ j = l + \frac{1}{2}\]
The e-probe revolution

First “picture” of a “single particle” evolving inside the nucleus

could be revealed only with high q transfers
(higher sensitivity to the most inner parts of the charge distribution)

revealed in medium effects
(how far a “single particle” is from a free nucleon)

• part of the single-particle quenching has “trivial” origins:
core (collective) couplings, many-body correlations

• short-range correlations, non-local part of the potential
→ effective mass of the nucleon,
→ neutron skin and giant haloes formation

B. Frois et al
in Modern Topics in Electron Scattering
(World Scientific 1991)
The e-probe revolution

First “picture” of a “single particle” evolving inside the nucleus

- part of the single-particle quenching has “trivial” origins: core (collective) couplings, many-body correlations

- **short-range correlations**, non-local part of the potential
  \[\rightarrow\] effective mass of the nucleon,
  \[\rightarrow\] neutron skin and giant haloes formation
Far from stability \(\rightarrow\) (hot) example: bubble nuclei

**A proton density bubble in the doubly magic \(^{34}\text{Si}\) nucleus**

A. Mutschler\textsuperscript{1,2}, A. Lemasson\textsuperscript{2,3}, O. Sorlin\textsuperscript{2,4}, D. Bazin\textsuperscript{5}, C. Borcea\textsuperscript{6}, R. Borcea\textsuperscript{6}, Z. Dombrádi\textsuperscript{6}, J.-P. Ebran\textsuperscript{7}, A. Gade\textsuperscript{8}, H. Iwasaki\textsuperscript{9}, E. Khan\textsuperscript{10}, A. Lepailleur\textsuperscript{11}, F. Recchia\textsuperscript{12}, T. Rogers\textsuperscript{13}, F. Rotaru\textsuperscript{13}, D. Sohler\textsuperscript{16}, M. Stanoli\textsuperscript{1}, S. R. Stroberg\textsuperscript{4,8}, J. A. Tostevin\textsuperscript{12}, M. Vandebruck\textsuperscript{1}, D. Weisshaar\textsuperscript{2} and K. Wimmer\textsuperscript{3,10,11}

**Ab initio calculation of the potential bubble nucleus \(^{34}\text{Si}\)**

T. Duguet\textsuperscript{1,2,3,*}, V. Somà\textsuperscript{1,1}, S. Lecluse\textsuperscript{2,1}, C. Barbieri\textsuperscript{4,8} and P. Navrátíl\textsuperscript{5,11}

\textsuperscript{1}IRFU, CEA, Université Paris-Saclay, 91191 Gif-sur-Yvette, France

\textsuperscript{2}KU Leuven, Instituut voor Kern- en Stralingsfysica, 3001 Leuven, Belgium

\textsuperscript{3}National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA

\textsuperscript{4}Department of Physics, University of Surrey, Guildford GU2 7XH, United Kingdom

\textsuperscript{5}TRIUMF, 4004 Westbrook Mall, Vancouver, British Columbia V6T 2A3, Canada

(Received 25 November 2016; published 23 March 2017)

**ab-initio calculations**

Central depletion reflects in larger \(|F(\theta)|^2\) for angles \(60^\circ<\theta<90^\circ\) and shifted 2nd minimum by \(20^\circ\)
not to mention:

- perfect coulomb excitation: forward electron scattering (no multi-step process)

- clean single nucleon knock-out (quasi-free)

- Excitation of collective modes (PDR etc)

- fission studies (condition on electron energy would give precise information of the initial condition of the fissioning system)

The possible physics program spans exactly the physics interests of the vast majority of the low-energy nuclear physics community in Orsay-Saclay (and in France) … with a much more powerful probe!
• all interesting phenomena occur at $q \gtrsim 2\text{fm}^{-1}$; the higher the $q$ transferred the lower the cross section; consider previous achievements in this domain $\Rightarrow$ compromise $E_e \approx 500\text{ MeV}$

• Luminosity:

$$L = \frac{F_e n_e N_A}{4\pi \sigma_x \sigma_y} = \frac{I_e N_A}{4 \pi \sigma_x \sigma_y q_e}$$

$\Rightarrow$ the aimed luminosity should be $10^{29}\text{ cm}^{-2}\text{s}^{-1}$
but much can be already done at $\mathcal{L} \approx 10^{28}$ (with unstable nuclei EVERYTHING is new !)

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Deduced quantity</th>
<th>Type</th>
<th>Luminosity [cm$^{-2}$s$^{-1}$]</th>
</tr>
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<tbody>
<tr>
<td>Elastic scattering at small $q$</td>
<td>r.m.s. charge radii</td>
<td>Light</td>
<td>$10^{24}$</td>
</tr>
<tr>
<td>First minimum in elastic form factor</td>
<td>Density distribution with 2 parameters</td>
<td>Light</td>
<td>$10^{28}$</td>
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<tr>
<td></td>
<td></td>
<td>Medium</td>
<td>$10^{26}$</td>
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<td></td>
<td></td>
<td>Heavy</td>
<td>$10^{24}$</td>
</tr>
<tr>
<td>Second minimum in elastic form factor</td>
<td>Density distribution with 3 parameters</td>
<td>Medium</td>
<td>$10^{29}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heavy</td>
<td>$10^{26}$</td>
</tr>
<tr>
<td>Pygmy/Giant resonances</td>
<td>Position, width, strength, decays</td>
<td>Medium</td>
<td>$10^{28}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heavy</td>
<td>$10^{28}$</td>
</tr>
<tr>
<td>Quasi-elastic scattering</td>
<td>SF, spectral strength</td>
<td>Light</td>
<td>$10^{39}$</td>
</tr>
</tbody>
</table>

• strategy: fixed target $\rightarrow$ trapped RI population $10^6$-$10^8$
Beams available today at ALTO – 0.5 kW primary e-beam

Tandem building
Institut de Physique Nucléaire
Campus of the Paris Sud University Orsay (France)
Beams available today at ALTO – 0.5 kW primary e-beam

- **e-LINAC**
  - 10 µA 50MeV
  - 0.5 kW
  - (former 1st section of the CERN LEP injector)

- **TIS vault**
  - ~10^11 fissions/s

- **PARRNe**
  - mass separator

- **Hall 110**
  - experimental setups

- **secondary beam lines**

- **kicker - bender**

- **beta decay spectroscopy**

- **Target Ion-source ensemble**
  - (30 keV ex)
Beams available today at ALTO

Measured productions yields at the detection point on line with the PARRNe mass separator electrons -> gamma induced fission

nominal intensity:
$10 \mu A \Rightarrow 10^{11}$ fissions/s

Production pps / 10 µA e-

- $5 \times 10^8 - 5 \times 10^9$
- $10^8 - 5 \times 10^8$
- $5 \times 10^7 - 10^8$
- $10^7 - 5 \times 10^7$
- $5 \times 10^6 - 10^7$
- $10^6 - 5 \times 10^6$
- $5 \times 10^5 - 10^6$
- $10^5 - 5 \times 10^5$
- $10^4 - 10^5$
- Stable

Systematic yield measurements made in June 2006

Hot plasma ion source
100 nA electrons
50 MeV
The SCRIT (Self-Confining Radioactive Ion Target) example


Location of the SCRIT Facility in the RIKEN RI Beam Factory

taken from: M. Wakasugi Workshop on e-Ion collision at CEA Saclay (25-27 Apr. 2016)
The SCRIT (Self-Confining Radioactive Ion Target) example

Construction from 2010 – 2011: Feasibility test of SCRIT
2014: New SCRIT device was installed. WiSES and Luminosity Monitor completed.
2015-2016: commissioning

Luminosity Monitor
Csl array

SCRIT Target system

RTM (Racetrack Microtron)

ERIS
ISOL
Ion transportation system

SR2 (Max. 700 MeV)
Electron energy: 100–300 MeV
Storage current: ~300 mA
Beam life time: >1 hours

WiSES
Scattered electron spectrometer
Acceptance: ~ 80 msr, (θ: 30-55 deg)
dp/p: ~ 10^-3 (Ee=300 MeV)

taken from: T. Tsukuda
Workshop on e-Ion collision at CEA Saclay
(25-27 Apr. 2016)
The SCRIT (Self-Confining Radioactive Ion Target) example

adapted from: M. Wakasugi
Workshop on e-Ion collision at CEA Saclay
(25-27 Apr. 2016)
The SCRIT (Self-Confining Radioactive Ion Target) example

Rear drift chamber

Dipole: 0.4 T for 150 MeV

Front drift chamber

T Ohnishi et al
Chancé et al (CEA Saclay) ETIC project within GANIL-2025 (2015) calculations within ERL hypothesis: \( I_e = 200 \text{ mA} \), \( N_A = 10^6 \) trapped ions: \( \mathcal{L} \approx 10^{29} \) should be achieved based on [A.N. Antonov et al., Nucl. Instr. and Meth. A 637 60 (2011)] ELISE project GSI

**PERLE@Orsay**: 20 mA → \( \mathcal{L} \approx 10^{28} \) is *probably* achievable for a \( 10^6 \) trapped RI population on the principle but the dynamical e-beam-RI coupling should be investigated: first time with a ERL time structure e-beam instabilities? impact on ERL operation?

**Production pps**

- Present \( \sim 10^{11} \) fissions/s
- E-beam 50 MeV 10 \( \mu \text{A} \)

- Second version of ALTO (yet no INB scenario)
  - E-beam 45 MeV 100 \( \mu \text{A} \) → \( \mathcal{L}_{\text{RIB}} \times 10 \)
International context/competition

ELISE @ FAIR
not funded yet (if ever?)

SCRIT @ RIKEN
present luminosity limitations \((10^{27})\)
RI target Z diversity ?

Storage ring at HIE-ISOLDE
abandoned

ETIC proposal within GANIL2025
not retained

At Orsay : long, well established know-how on:
• electron acceleration
• electron detection
• Radioactive Ion Beam ISOL-production
• Radioactive Ion Beam manipulation & trapping
and a large nuclear physics users community!
Conclusion

So... what are we waiting for?

thank you for your attention